Inclusion of carbonation during the life cycle of built and recycled concrete: influence on their carbon footprint

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Abstract

Background, aim, and scope When the service life (or primary life) of built concrete infrastructure has elapsed, a common practice is that the demolished concrete is crushed and recycled, then incorporated into new construction. LCA studies of CO_2 emissions focus on the manufacturing and construction and occupancy/utilization phases, without consideration of the demolition and application of recycled concrete into a secondary construction application. Concrete has a documented ability to chemically react with airborne carbon dioxide (CO_2); however, carbon capture (or carbonation) by concrete during the primary and secondary life, is not considered in LCA models. This paper incorporates CO_2 capture during both primary and secondary life into an LCA model for built concrete.

Materials and methods CO_2 equivalent (CO_2-e) emissions were estimated by calculation of the quantity of CO_2-e emitted per unit of activity at the point of emission release (i.e., fuel use, energy use, manufacturing activity, construction activity, on-site demolition, etc.). Carbonation was estimated for built concrete during the primary life and also during the secondary life when the demolished concrete structure is crushed and recycled for a new application within a new built structure. Life cycle calculations for a built bridge structure are provided which contrasts the net effects of CO_2 emission and capture. The study has analyzed a concrete bridge with primary life of 100 years. Following completion of the primary life, we have considered that the demolished concrete from the bridge will be crushed, recycled, and used in the construction of a replacement bridge. Due to damage caused by demolition and crushing, the quality of the recycled concrete is unlikely to be as high as quarried natural rock, and the recycled concrete is most likely to be used in a more temporary construction application with an assumed 30-year secondary life. Following the expiry of the secondary life, if recycling of recycled concrete aggregate (RCA) was to be undertaken, it is unlikely the quality of RCA will be suitable to enable a third construction application: therefore, our LCA includes the primary life of 100 years plus the secondary life of 30 years.

Results Carbonation of the built concrete during the primary life is almost negligible compared with the emissions arising from manufacture of raw materials, concrete production, and construction. However, CO_2 capture by recycled concrete during the secondary life is considerably greater: a factor that is not included in LCA estimates of the carbon footprint of built concrete. Crushed concrete has considerably greater exposed surface area, relative to volume, than a built concrete structure: therefore, a greater surface area of RCA, compared with a built structure, is exposed to CO_2 and carbonates. This key factor leads to such high amounts of carbonation during the secondary life when compared with the built structure.

Discussion While reducing the amount of solid landfill, recycled concrete provides significant capture of airborne carbon dioxide. The effects of carbon capture of recycled concrete aggregate within the secondary life is significant, imbibing up to 41% of the CO_2 emitted during manufacture of a 100% Portland cement binder. Emission estimates can be overestimated by as much as 13–48%, depending on the type of cementitious binder in the built concrete and the application of recycled concrete during the secondary life.

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The effects of carbon capture of recycled concrete aggregate within the secondary life are significant and should be included in LCA calculations for reinforced concrete structures.

Conclusions Carbonation during the secondary life can be affected by the type of application and exposure of the RCA: gravel with fine particle size will carbonate more comprehensively than larger boulders (due to greater exposed surface area), while air-exposed RCA will carbonate more comprehensively than RCA located in a buried and moist environment. An approach is provided in this paper that incorporates carbon capture by concrete infrastructure into LCA carbon emission calculations. If carbonation is ignored, emission estimates can be overestimated by 13–48%, depending on the type of cement binder and the application of RCA during the secondary life.

Recommendations and perspectives Due to the considerable number and types of built concrete structures, it is recommended that the LCA model be improved by incorporation of carbonation data obtained from recycled concretes that have been applied to a variety of construction applications and exposed to a range of exposure environments.

1 Background, aim, and scope

Australia generates 32.3 million tonnes of solid waste annually and concrete is by far the most recycled construction material, with waste concrete sourced from the construction and demolition industries (Harper 2006). Recycled waste concrete can be utilized as a construction material, for example as unbound rock or gravel for use as embankment protection or sub-base for pavements. While reducing the amount of solid landfill, recycled concrete poses a further advantage when considering carbon emissions over the life cycle of a built concrete structure: carbon capture, or carbonation, of airborne carbon dioxide (CO_2). Carbonation of concrete while in service has been previously researched, primarily to address the problem of corrosion of embedded steel reinforcement; however, the contribution of carbonation towards estimation of CO_2 emissions over the life cycle is generally not considered in LCA estimates (Xinga et al. 2008; Guggemos and Horvath 2005; Flower and Sanjayan 2007; Vieira and Horvath 2008; Horvath and Hendrickson 1998; Naik 2008). The more comprehensive carbonation of recycled concrete due to the greater exposed surface area to atmospheric CO_2 (Pade and Guimaraes 2007) is mostly not considered in LCA calculations.

The objective of this paper is to examine the contribution of carbonation to the estimation of equivalent CO_2 emissions over the life cycle of a concrete structure. The life cycle includes both the primary life of the built concrete structure and also during the secondary life which includes the demolition, recycling, and re-use of concrete in a construction application. A case study provides an LCA of a built concrete bridge.

2 Materials and methods

2.1 Research structure

The research followed these main steps:

1. Estimation was made of CO_2-e emissions (i.e., CO_2 equivalent emissions) arising due to manufacture of raw materials, concrete construction activities, occupancy, and operation and maintenance during the service life, and eventual demolition at the end of the service life. Calculations were based on the quantity of CO_2-e per unit of activity at the point of emission release (i.e., fuel use, energy use, manufacturing process activity, construction activity, on-site demolition, etc.).
2. CO_2 capture by carbonation during the life cycle of the built concrete was assessed.
3. Estimation of carbonation by recycled concrete, including the sensitivity of different re-use options, was made.
4. LCA calculations were undertaken of CO_2-e of a concrete component of a built bridge.
5. Evaluation was conducted of the significance of carbonation on LCA estimates of carbon emissions.

2.2 Primary and secondary life

2.2.1 Definitions

The life cycle can be divided into primary and secondary life (Fig. 1). The primary life extends from the time of extraction of raw materials for concrete manufacture to the completion of demolition of the built structure. The secondary life commences when concrete is recycled and is utilized in new construction, and it reaches the conclusion when the built component reaches the end of the service life. Figure 1 summarizes the main features of the primary and secondary life, together with sources of CO_2 emissions, CO_2 savings, and CO_2 capture by carbonation.

2.2.2 Case of a built concrete bridge

The study has analyzed the life cycle CO_2 emissions generated by a built concrete component of a bridge,
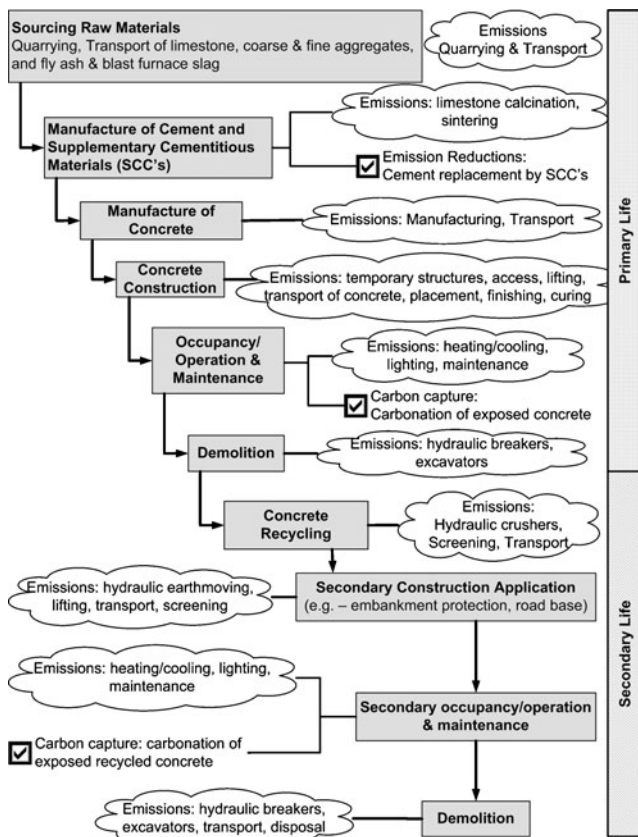
Fig. 1 Life cycle aspects of CO_2 emissions and carbon capture in concrete

designed to the Australian Bridge Design Standard AS5100 (Standards Australia International 2004), with specified primary life of 100 years. Following completion of the primary life, we have considered the demolished concrete from the bridge will be crushed, recycled, and used in the construction of a replacement bridge. Due to damage caused by demolition and crushing, the quality of the recycled concrete is unlikely to be as high as quarried natural rock, and the recycled concrete is most likely to be used in a more temporary construction application with an assumed 30-year secondary life. Following the expiry of the secondary life, if recycling of recycled concrete aggregate (RCA) was to be undertaken, it is unlikely that the quality of RCA will be suitable to enable a third construction application: therefore, our LCA includes the primary life of 100 years plus the secondary life of 30 years.

2.3 CO_2-e emissions due to manufacture of raw materials and concrete construction

2.3.1 Calculation of CO_2-e

LCA studies report the estimated quantities of CO_2-e during manufacture of concrete-making materials and construction

activities (Xinga et al. 2008; Guggemos and Horvath 2005; Flower and Sanjayan 2007; Vieira and Horvath 2008; Horvath and Hendrickson 1998; Naik 2008). Figure 1 shows the main contributors to CO_2 emissions during manufacturing and construction: arising from quarrying and crushing, transport of raw materials to the manufacturing premises, manufacture of cementitious materials and aggregates, concrete making and transport by mobile agitator to the construction site, and concrete construction activities (including provision of temporary formwork and support and access structures, concrete placement, finishing, and curing). Manufacture of cement is a major contributor to CO_2 emissions due to the high energy demands during manufacturing and also the calcination of limestone, one of the main raw ingredients of cement, which leads to further emission of CO_2. Cement can be partly substituted by supplementary cementitious materials (SCC), which commonly include ground granulated blast furnace slag, a waste by-product from steelmaking, and fly ash, a fine waste residue that is collected from the emissions liberated by coal burning power stations. Figure 1 shows SCCs as contributors to the reduction of CO_2 emissions due to the partial replacement of cement. Emission estimates depend on local conditions at the source of raw materials, manufacturing premises, and construction site, such as climate, energy sources, and transportation distances. CO_2-e arising from raw materials and construction are based on Flower and Sanjayan (2007) and Australian National Greenhouse Accounts (NGA) Factors Workbook (Commonwealth of Australia 2008).

2.3.2 Case of a built concrete bridge located in Melbourne, Australia

The case examines locally sourced concrete construction materials within Melbourne, Australia. The equivalent emission factors estimated for each of the concrete making materials are summarized in Table 1. The sensitivity of using four different locally used cementitious binder types have been assessed, namely 100% Ordinary Portland Cement (OPC), 65% ground granulated blast furnace slag (slag)/35% OPC; 35% slag/65% OPC, and 20% fly ash (FA)/80% OPC.

Table 1 CO_2 emission factors evolved from manufacturing of concrete making materials and construction activities

Concrete making material	Emission factor (t CO_2-e/tonne)
Ordinary Portland cement (OPC)	0.82
Ground granulate blast furnace slag	0.143
Fly ash	0.027
Coarse aggregates	0.0459
Fine aggregates	0.0139

The fine and coarse aggregates are assumed to be locally quarried basalt and river sand. The concrete mixture for bridge construction is assumed to be 40 MPa strength and total cementitious content of 400 kg/m^3.

The case examines construction of a crosshead beam that is part of a two-span concrete bridge. The beam supports the overlying deck. The beam will be built at height where energy will be expended due to provision of temporary structural support and access, manufacture and transport, and pumping, placement, finishing, and curing of the concrete. The equivalent emission factors estimated for each of the concrete construction activities are summarized in Table 2.

2.4 CO_2 capture by concrete during primary life

2.4.1 Influencing factors

Concrete has a documented ability to chemically react with carbon dioxide, referred to as carbonation (Verbeck 1958; Cole and Kroone 1960; Ho and Lewis 1987; Bickley 1990; Jones et al. 2000; RILEM Committee TC. 56 1988; and Tuutti 1982). Gaseous CO_2 penetrates into concrete by diffusion through unsaturated concrete pores and reacts with solutes within the pores (mostly calcium hydroxide). During the service life of a built concrete structure, concrete progressively carbonates with increasing depth. Influencing factors include diffusivity of concrete to CO_2 and the constituents of the cementitious binder. The exposure environment is also critical, including temperature, CO_2 concentration, and relative humidity. Past investigations of carbonation focused on corrosion initiation of embedded steel within concrete, arising from depletion of concrete alkalinity by carbonation, leading to the breakdown of the protective iron oxide film on the steel surface. Corrosion initiation by carbonation is a significant factor affecting concrete durability; however, assuming corrosion durability of the embedded steel has been designed and built into the structure, the focus of this paper is to quantify the influence of carbonation on CO_2 emission estimates.

2.4.2 Carbonation modeling

Predictive models are based on Fick's 1st Law of Diffusion, whereby the depth of carbonated concrete, x, is proportional

Table 2 CO_2 emission factors evolved from concrete construction activities

Construction activity	Emission factor (t CO_2-e/tonne)
Concrete batching and mixing	0.82
Concrete transport	0.143
Concrete placement	0.027

to the CO_2 concentration difference arising between the air-exposed concrete surface, C_{ext}, and the internal concrete, C_{int}. The mass, m, of CO_2 diffusing through the exposed concrete is expressed as follows:

$$m = \frac{DA(C_{ext} - C_{int})t}{x} \qquad (1)$$

Where A is the exposed surface area of concrete and D is the coefficient of diffusion of CO_2 through the concrete (square meter per second). For the carbonation of the alkaline components within a unit volume of concrete, a mass per unit volume of, say, b kg/m^3 of CO_2 is needed. To increase the depth of carbonation by an increment, dx meters, and the mass of CO_2 that is required is:

$$m = bAdx \qquad (2)$$

inserting (2) into (1):

$bAdx = \frac{DA(C_{ext} - C_{int})t}{x}$ and, following re-arrangement:

$$xdx = \frac{D}{b(C_{ext} - C_{int})t} \qquad (3)$$

Integration of (3) enables a simplified expression of x, the depth of carbonated concrete:

$$\int_0^x xdx = \frac{x^2}{2} = \frac{D}{b}(C_{ext} - C_{int})t \qquad (4)$$

If the constant parameters are combined into a single constant, k, the depth of carbonated concrete, x, is simplified into the following equation:

$$x = \sqrt{\frac{2D}{b}(C_{ext} - C_{int})t} = k\sqrt{t} \qquad (5)$$

The constant, k, is commonly referred to as the "carbonation rate coefficient" that collectively includes the physical and chemical characteristics of the concrete and of the environment and is either determined experimentally or measured on built structures.

2.4.3 Carbonation case of a built concrete bridge

The case has analyzed the CO_2 emissions from a concrete crosshead beam that supports the overlying deck of a bridge. In our estimates, we have made the following assumptions:

1. Primary life is 100 years, based on AS5100 (Standards Australia International 2004)
2. The CO_2 content of the surrounding air is 0.037% (Coutts et al. 2007), based on the average of measurements taken within Melbourne CBD, although it is acknowledged that the concentration will vary within Melbourne and throughout Australia.

3. The concrete mixture is based on 28-day concrete strength of 40 MPa and total cementitious content of 400 kg/m^3.
4. The CaO content of the OPC was assumed to be 65% (Collins and Sanjayan 2008).
5. Concrete has a k coefficient of 3.9 mm year$^{0.5}$ (Ho and Lewis 1987) in the case of the binder consisting of 100% OPC. Account was taken for binder composition which affects the rate of carbonation: the k-coefficient was multiplied by 1.15, 1.1, and 1.1 for 65% slag/35% OPC, 35% slag/65% OPC, and 20% FA/80% OPC, respectively (Ho and Lewis 1987, Lagerblad 2005).

The carbon dioxide uptake (kilograms) during the primary life was calculated as follows:

$$CO_{2(\text{uptake kg})} = x \cdot c \cdot CaO \cdot r \cdot A \cdot M \qquad (6)$$

where x is the calculated depth of carbonation (meters), c is the quantity of OPC within the binder (kilograms per cubic meter proportioned in the case of blended slag or fly ash binders), CaO is the calcium oxide content within OPC (assumed to be 0.65; where 1.0 represents 100% CaO content), r is the proportion of CaO within fully carbonated OPC that converts to CaCO$_3$ (dimensionless and assumed to be 0.75 (Lagerblad 2005); where 0 indicates zero conversion and 1.0 indicates total conversion), A is the exposed surface area of concrete (square meters), and M is the dimensionless chemical molar fraction, CO$_2$/CaO, or 0.79.

2.5 CO$_2$-e during primary life arising from occupancy, operation, and maintenance

Depending on the type and application of the built concrete structure or component, CO$_2$ emissions will arise from occupancy and operation (e.g., heating/cooling/lighting) and maintenance activities. These issues are important, particularly when comparing concrete with other types of construction materials and differences will arise on a case-by-case basis. However, in the case study of a bridge structure, minimal contributions to CO$_2$-e are assumed, whereas a commercial building would have significant energy demands and much higher CO$_2$-e.

2.6 CO$_2$-e due to demolition and recycling

At the expiry of the primary life, CO$_2$ emissions arise from energy expended on demolition of the built structure. Our estimates assume demolition will be by mobile boom-mounted pneumatic breakers. RCA will be manufactured on-site using portable equipment and re-used in the construction of a replacement bridge, thereby minimizing CO$_2$ emissions resulting from transportation to/from a recycling plant. The study examines two types of application

of the recycled concrete: (1) large boulders serving as embankment protection and (2) application as road sub-base gravel for the approaches to the bridge. Diesel-powered hydraulic primary jaw crushers will produce boulder-sized RCA and gravel-sized RCA for road sub-base will have undergone secondary crushing, followed by screening. Finally, diesel haulers move the final graded products into stockpiles for use in construction. CO$_2$-e estimates were based on the Australian National Pollutant Inventory Emission Estimation Technique Manual for Mining Version 2.3 (Commonwealth of Australia 2001) and emission factors that were utilized in our estimates are summarized in Table 3.

2.7 CO$_2$ capture during secondary life

2.7.1 Carbonation of crushed recycled concrete

Few studies deal with carbonation of recycled concrete. Investigation of carbonation of recycled concrete within Nordic countries (Pade and Guimaraes 2007; Lagerblad 2005; Christian et al. 2005; Pommer and Pade 2005) showed that RCA carbonates more significantly than built concrete. Crushed concrete has considerably greater exposed surface area, relative to volume, than a built concrete structure: therefore a greater surface area of RCA, compared with a built structure, is exposed to CO$_2$ and carbonates. Lagerblad (2005) has determined that 75% of the calcium oxide within OPC can react and convert to calcium carbonate if sufficient time and exposure is provided. Recent XPS analysis of recycled concrete aggregate (Haselbac and Ma 2008) indicates the uptake of CO$_2$ could be even 30% higher than the stoichiometric equivalent; however, the authors concluded that further detailed analysis is needed.

2.7.2 Case estimation of CO$_2$ capture during secondary life

Two common construction applications were considered for the recycled concrete:

Recycled concrete crushed into 200-mm boulders and serving as embankment protection. The boulders would be placed beneath the abutment of the new bridge and are

Table 3 CO$_2$ emission factors due to demolition and recycling

Activity	Emission factor (t CO$_2$ e/tonne)
Demolition (mobile rock breaker)	0.00054
Primary jaw crushing	0.00020
Secondary crushing (gravel only)	0.00060
Screening	0.00008
Loading stockpiles	0.00006

essentially in a similar exposure environment to the original concrete element (sheltered by the overlying deck). The RCA boulder shape was approximated as spherical, although the concrete source, method of crushing, and surface roughness will affect estimates of surface area and volume.

Recycled concrete crushed to finer-sized gravel to be applied as road sub-base. The recycled concrete is exposed to buried and moist exposure conditions and the carbonation k-coefficient is expected to be considerably less due to high humidity within the concrete ($k=$ 1.5 mm year$^{0.5}$ was assigned). Table 4 summarizes the size distribution of RCA gravel.

3 Results

The results are summarized in Table 5. Calculations were based on CO_2 equivalent (CO_2-e) emissions were estimated by calculation of the quantity of CO_2-e emitted per unit of activity. The calculations were based on a concrete mixture composed of the following (to make 1 m^3 of concrete): cement 400 kg/m^3, coarse aggregate 995 kg/m^3, coarse sand 555 kg/m^3, fine sand 175 kg/m^3, and water 175 kg/m^3.

3.1 Emissions arising from manufacture of raw materials and concrete construction

The key source of CO_2-e relate to Portland cement manufacture, which echoes previous studies. Significant reductions in emissions were achieved using slag or fly ash blended cements, with reductions as high as 54% in the case of the binder 65% slag/35% OPC. Significant reductions were also achieved during manufacture of the other blended cements that were reviewed, namely 29% and 19% in the cases of binders comprising 35% slag/65% OPC and 20% fly ash/80% OPC, respectively. Although fly ash has a lower CO_2-e factor than slag, the quantity of OPC within the binder that can be replaced by fly ash on bridge structural concrete

is less than slag because of issues related to early age strength. Manufacturing of fine and coarse aggregates have less emissions than production of cementitious binders (15–37%), despite quarrying that entails blasting, crushing, screening, haulage, and stockpiling of aggregates.

The contribution to emissions during the concrete production and construction stage is relatively small compared with manufacture of the raw materials, amounting to 13% to 24% of the CO_2-e arising from the manufacture of cementitious binders and aggregates. The emissions will vary depending on transportation distance from the concrete plant to the construction site as well as the complexity of construction and the remoteness of the project site.

3.2 Carbon capture during primary life of the built structure

Table 5 shows carbonation during the primary life is almost negligible. This is to be expected since the geometry of a concrete crosshead beam of a bridge has relatively small surface area exposed compared with 1 m^3 volume of concrete. Lower quality concrete can be expected to carbonate to greater depths, although unlikely to be significant, notwithstanding the need for quality of the concrete to meet the 100-year durable service life of the bridge.

3.3 Emissions due to demolition and recycling

Table 5 shows minor CO_2-e arising during demolition and concrete recycling activities.

3.4 Carbon capture during secondary life

Carbonation during secondary life was considerably greater than during primary life (see Table 5). The greatest influence occurs where RCA is applied as a road sub-base. Despite considerably reduced carbonation rate due to the buried and moist exposure, the calculations nevertheless show almost all particles achieve full carbonation. This was not the case for boulder-sized embankment protection, where the higher exposed surface area to volume (per boulder) leads to smaller portions of carbonated concrete during secondary life. Carbonation of RCA within the secondary life is significant, imbibing up to 41% of the CO_2-e during manufacture of a 100% Portland cement binder.

4 Discussion

A bridge designed to the Australian Bridge Design Standard AS5100 has a specified service life of 100 years

Table 4 Estimates of life cycle CO_2 emissions/carbon capture generated by 1 m^3 of concrete over the primary and secondary life

Particle size (mm)	Proportion of total (%)
19.0–26.5	1
13.2–19.0	11
9.5–13.2	13
4.75–9.5	22
2.36–4.75	12
0.425–2.36	22
0.075–0.425	12
<0.075	6

Table 5 Size distribution of RCA gravel

Source of emission/carbon capture	Emissions (kg CO_2-e) per binder type			
	100% OPC	65% slag/35% OPC	35% slag/65% OPC	80% OPC/20% fly ash
Manufacturing cementitious materials	328.0	152.0	233.2	264.6
Manufacture fine and coarse aggregates	55.8	55.8	55.8	55.8
Concrete production and construction	50.6	50.6	50.6	50.6
Carbonation of built concrete over primary life	−4.6	−1.8	−3.3	−4.0
Demolition and recycling	1.9	1.9	1.9	1.9
Option 1: carbonation of RCA used as rip-rap embankment	−85.7	−34.6	−61.3	−75.5
Option 2: carbonation of RCA used as gravel road sub-base	−136.2	−123.5	−128.3	−130.6
Total (including option 1)	346.0	223.9	276.9	293.4
Total (including option 2)	295.5	135.0	209.9	238.3

which is the same time horizon employed by most LCA studies. Following completion of the 100 years, we have considered the case of the demolished concrete from the bridge will be crushed, recycled, and used in the construction of a replacement bridge. Due to damage caused by demolition and crushing, the quality of the RCA is unlikely to be as comparatively high as quarried natural rock, and therefore RCA is most likely to be used in a more temporary construction application with an assumed secondary life of 30 years. Following the expiry of the secondary life, if recycling of RCA was to be undertaken, it is unlikely the quality of RCA will be suitable to enable a third construction application: therefore, our LCA includes the primary life of 100 years plus the secondary life of 30 years.

Crushed concrete has considerably greater exposed surface area, relative to volume, than a built concrete structure: therefore, a greater surface area of RCA, compared with a built structure, is exposed to CO_2 and carbonates. This key factor leads to such high amounts of carbonation during the secondary life when compared with the built structure.

LCA calculations for built concrete infrastructure seldom account for carbonation during the secondary life when the concrete from the primary structure is recycled and re-used. If carbonation is ignored, the emission estimates can be overestimated by as much as 13–48%, depending on the type of cement binder and the application of RCA during the secondary life.

Nevertheless, the key source of CO_2 emissions relates to manufacture of Portland cement. Significant reductions in emissions can be achieved by partly substituting Portland cement with fly ash or slag, with reductions as high as 54% in the case of a binder comprising 65% slag and 35% OPC.

While reducing the amount of solid landfill, recycled concrete provides significant capture of airborne carbon dioxide. The effects of carbon capture of recycled concrete

aggregate within the secondary life are significant and should be included in LCA calculations for reinforced concrete structures.

5 Conclusions

This paper has re-examined the life cycle carbon footprint of concrete structures, specifically examining the contribution of carbon capture of CO_2, both during the primary life of a built concrete structure and, following demolition and subsequent recycling of the concrete, during the secondary life. LCA investigations on concrete structures do not account for carbonation of concrete, where atmospheric carbon dioxide chemically reacts with exposed concrete over the life of the structure, during the primary or secondary life. The study has analyzed the life cycle CO_2 emissions generated by a built concrete component of a bridge with primary life of 100 years. Following completion of the primary life, we have considered the demolished concrete from the bridge will be crushed, recycled, and used in the construction of a replacement bridge. Due to damage caused by demolition and crushing, the quality of the recycled concrete is unlikely to be as high as quarried natural rock, and the recycled concrete is most likely to be used in a more temporary construction application with an assumed 30-year secondary life. Following the expiry of the secondary life, if recycling of RCA was to be undertaken, it is unlikely the quality of RCA will be suitable to enable a third construction application: therefore, our LCA includes the primary life of 100 years plus the secondary life of 30 years.

Our findings have shown that, although carbonation of concrete during the primary life is relatively small, significant carbonation occurs during secondary life when the demolished concrete, broken into waste fragments and recycled, has a higher exposed surface area available to

react with CO_2. Carbonation during the secondary life can be affected by the type of application and exposure of the RCA: gravel with fine particle size will carbonate more comprehensively than larger boulders (due to greater exposed surface area), while air-exposed RCA will carbonate more comprehensively than RCA located in a buried and moist environment. An approach is provided in this paper that incorporates carbon capture by concrete infrastructure into LCA carbon emission calculations. If carbonation is ignored, emission estimates can be over-estimated by 13–48%, depending on the type of cement binder and the application of RCA during the secondary life.

6 Recommendations and perspectives

The effects of carbon capture by recycled concrete are significant over the lifecycle and should be considered when estimating net green house gas emissions for built concrete infrastructure. Due to the considerable number and types of built concrete structures, it is recommended that the predictive model be improved by incorporation of carbonation data from recycled concretes that have been applied to a variety of secondary life applications.

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